SLOT TRANSMISSION LINE

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SLOT TRANSMISSION LINE

by

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Slot Transmission Line

by

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ABSTRACT

A slot transmission line on a dielectric substrate has been proposed as an alternative to open microstrip line as a transmission line for microwave integrated circuits. Construction and measurement techniques suitable for this configuration are described. Experimental measurements of slot line parameters and a coaxial line-to-slot line transition from 10 MHz to 12 GHz are discussed. Insertion loss of a 2 inch length of slot line with coaxial transitions was found to be less than 5 dB from 400 MHz to 6 GHz, and the input VSWR was less than 2.0 from 1 GHz to 10 GHz.

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I. INTRODUCTION

Recently the slot line has been proposed as an alternative to open microstrip line as a transmission line for microwave integrated circuits [Ref. 1, 2, 3, 4]. The slot line configuration, shown in Fig. 1, consists of a narrow slot in the metal coating of a dielectric substrate. If the dielectric substrate has a sufficiently high dielectric constant (typically $\varepsilon_r \geq 9$) the fields will be tightly bound to the region of the slot and energy will propagate down the slot. A schematic representation of the fields in the slot line is presented in Fig. 2.

Several applications of slot line have been suggested. The elliptical fields lend themselves to use in ferrite

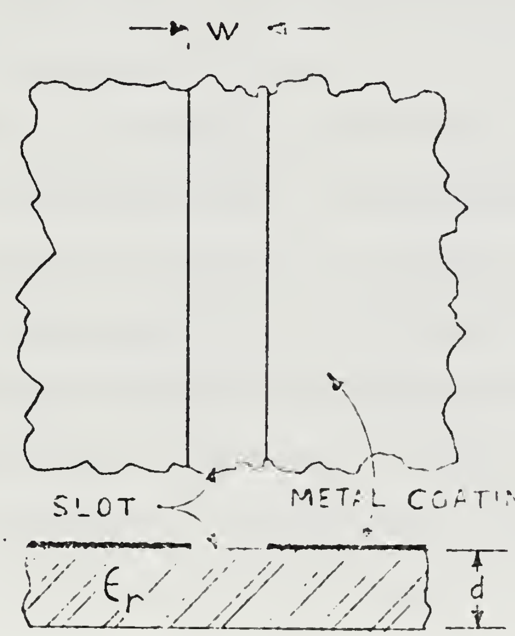

Figure 1. Slot Line Configuration.

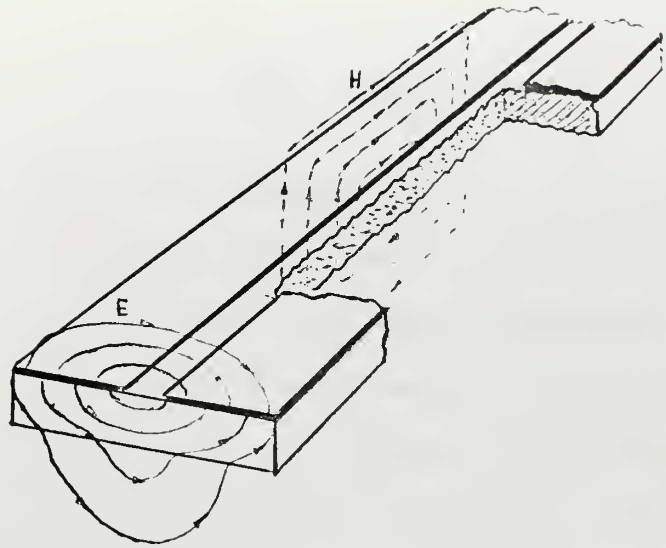

Figure 2. Schematic Representation of Fields in Slot Line.

phase shifters [Ref. 3]. The physical configuration of the slot line greatly simplifies shunt mounting of components such as diodes and the capability of realizing resonant circuits in slot line [Ref. 6] offers the possibility of entire microwave integrated circuits constructed in a slot line configuration. A properly flared slot line may also find application as a miniature, flush-mounted antenna.

The object of this thesis is to present the results of an experimental investigation of the characteristics of slot line. Particular emphasis was placed on construction methods, and measurement techniques. These techniques were applied to the experimental verification of the broad-band characteristics of a coaxial line-to-slot line transition.

II. THEORY

The basic electrical parameters of slot line are the characteristic impedance (Z_o) and the phase velocity (v). Since the slot wave is non-TEM, these parameters vary slowly with frequency in much the same manner as wave-guide parameters. However, the slot line differs from waveguide in that theoretically, it has no cutoff frequency. Cohn [Ref. 1] has derived a second-order solution for the electrical parameters of the slot line and several approximations that are useful.

A. SECOND-ORDER SOLUTION

An exact solution of the slot line problem would involve cylindrical coordinates [Fig. 3] and all orders of Hankel

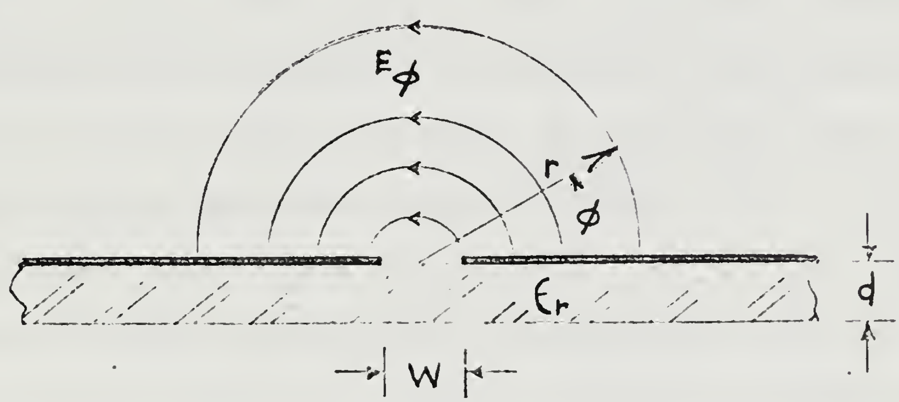

Figure 3. Cylindrical Coordinates with Axis on Center Line of Slot.

functions. Introduction of boundary walls permits the slot line to be treated as a rectangular waveguide problem rather than as a problem in cylindrical coordinates.

Assuming slot waves of equal amplitude traveling in the +x and -x (axial) directions gives transverse planes separated by $\lambda'/2$ where the transverse E field and normal H field are zero. An electric (conducting) wall can be placed at x=0 and $x=\lambda'/2=a$ without affecting the fields between the planes. If the substrate and conducting walls are assumed dissipationless, the section of slot line between the transverse planes will support a resonant slot wave mode with no loss of energy.

Since the fields are tightly bound to the vicinity of the slot, electric or magnetic walls can be placed at $y=\pm b/2$ for b/d sufficiently large (about 7.5). These boundary walls form a rectangular waveguide with a capacitive iris and air and dielectric regions as indicated in Figure 4.

Due to the non-TEM nature of the slot wave, definition of characteristic impedance is arbitrary. The definition chosen by Cohn for this derivation is $Z_o=V^2/2P$, where V is the peak voltage amplitude across the slot and P is the average power flow of the slot wave.

Based on these assumptions Cohn arrived at the following expressions for the ratio of phase velocity to group velocity and characteristic impedance.

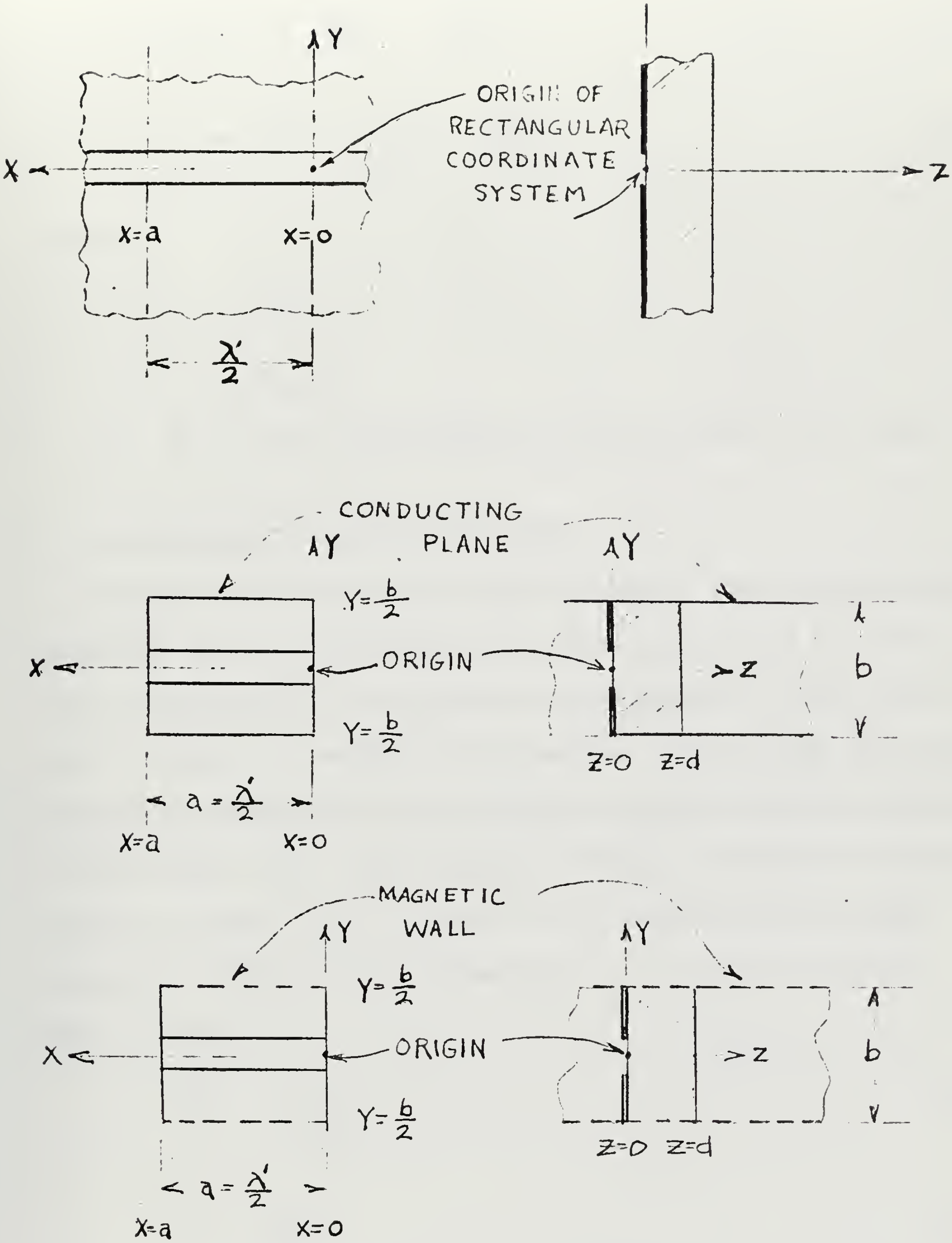

Figure 4. Waveguide Models for Slot Line Solutions. (a) Insertion of transverse electric walls at x=0 and a. (b) Insertion of electric walls at y=±b/2. (c) Insertion of magnetic walls at y=±b/2.

$$\frac{v}{v_g} = 1 + \frac{f}{\lambda/\lambda'} \cdot \frac{\Delta(\lambda/\lambda')}{\Delta f} \tag{1}$$

$$Z_o = 376.7 \frac{v}{v_g} \frac{\pi}{p} \cdot \frac{\Delta p}{-\Delta \eta B_t} \tag{2}$$

where

$p = \lambda/\lambda'$

$\eta = \sqrt{\mu_o/\varepsilon_o}$

B_t = total susceptance at the plane of the slot

B. APPROXIMATIONS FOR SLOT LINE

Cohn [Ref.1] has also derived useful zero-order approximations for the ratio of the guide wavelength to free space wavelength, the effective permittivity, the ratio of the voltage at a radius (r) from the slot to the voltage directly across the slot, and the characteristic impedance of the slot line. The results of this derivation are presented as Eqns. 3, 4, 5, and 6 and graphically as they relate to the physical parameters of the slot line in Refs. 2 and 6.

$$\frac{\lambda'}{\lambda} = \sqrt{\frac{2}{\varepsilon_r+1}} \tag{3}$$

$$\varepsilon_r' = \frac{\varepsilon_r+1}{2} \tag{4}$$

$$\frac{V(r)}{V} = \frac{\pi}{2} K_c r \, |H_1^{(1)}(K_c r)| \tag{5}$$

where

$$K_c = \sqrt{K^2+\gamma^2}$$

$H_1^{(1)}(K_c r)$ = Hankel function of argument $K_c r$

$$Z_o = \frac{591.7\ (\lambda'/\lambda)}{\ln\left(\frac{8b}{\pi w}\right)} \text{ ohms} \qquad (6)$$

C. EQUIVALENT CIRCUIT FOR TRANSITION

Experimental tests of slot line [Ref. 2 and 3] show that for a good broadband match to a 50 ohm coaxial line a slot line characteristic impedance of about 70 ohms is required. Explanations for this are:

> Since the slot wave is non-TEM, any definition of characteristic impedance cannot be unique. (Furthermore, reactive discontinuities may cause an impedance transformation.)

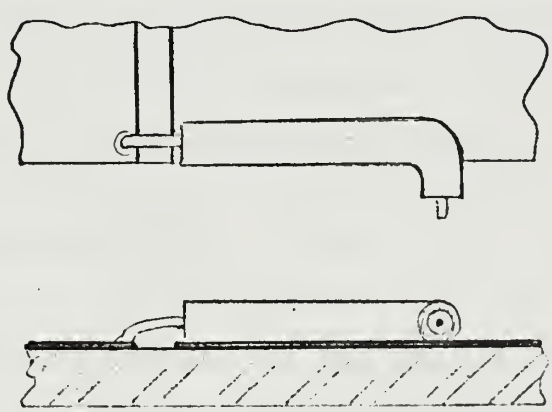

Figure 5. Coaxial-to-slot Line Transition.

Chambers, et al [Ref. 4] present an approximate derivation of an equivalent circuit for this transition. The derivation is based on an idealized model shown in Figure 6, consisting of a semicircular wire loop bridging the slot.

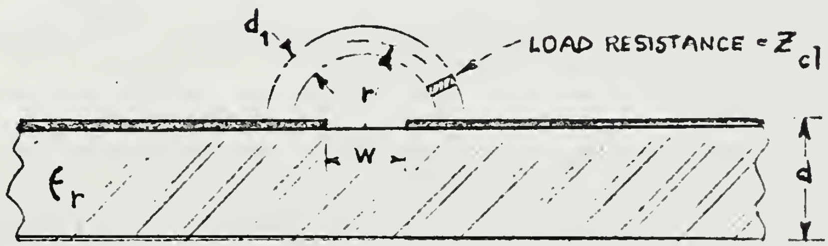

Figure 6. Idealized Model of Transition.

A lumped resistance equal to Z_{cl} (Z_o of the coaxial line) is in series with the loop. The center conductor diameter of the coaxial line is d_1, and the loop radius (r) is approximately equal to the mean radial distance from the slot's center to the center conductor. From this model the inductance of the loop is computed to be:

$$L = 15.95 \left(\ln \frac{16r}{d_1} - 2\right) \text{ nH} \qquad (7)$$

Further computation results in the equivalent circuit of Figure 7. The transformer ratio (n) is given by:

$$n = \frac{V(r)}{V} \qquad (8)$$

and can be computed from Eqn. 5.

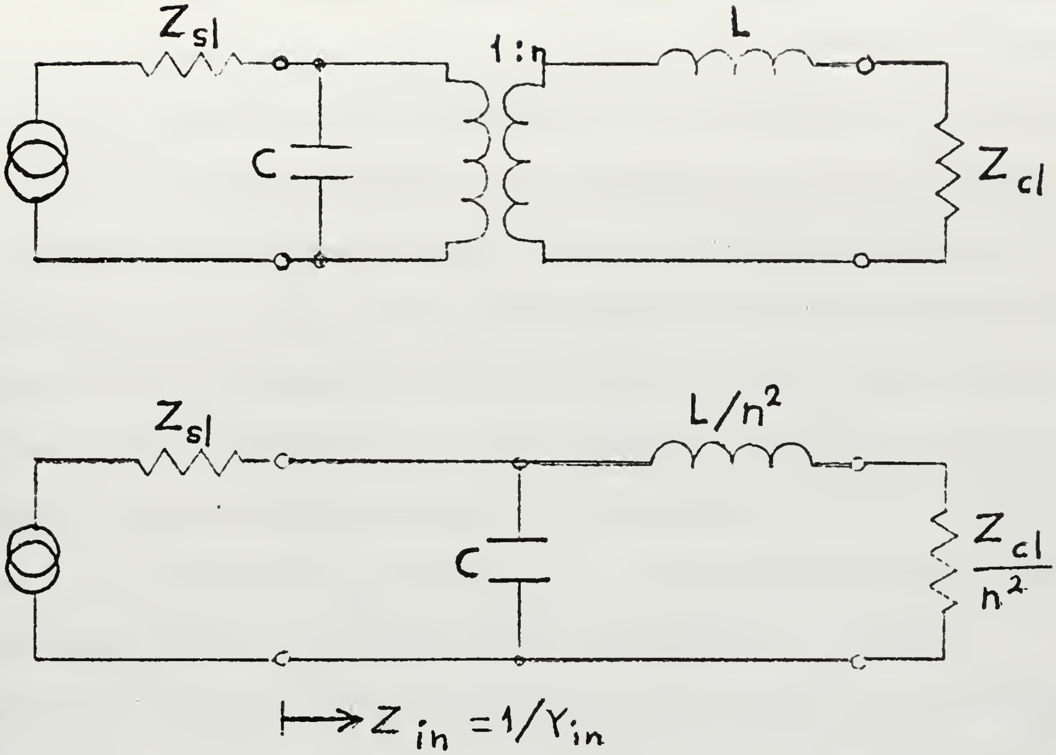

Figure 7. Equivalent Circuit of Slot Line to Coaxial Line Transition.

Removing the transformer from the circuit allows computation of the input impedance Z_{in}.

$$Z_{in} = Z_{c\ell}\left(\frac{1 + \left(\frac{\omega L}{Z_{c\ell}}\right)^2}{n^2}\right) + j^{o} \tag{9}$$

This shows that Z_{in} has indeed been increased compared to $Z_{c\ell}$.

D. CHARACTERISTICS OF SLOT LINE

In addition to the electrical parameters previously mentioned, there are three important physical parameters of slot line: the dielectric constant of the substrate (ε_r), the thickness of the substrate (d), and the width of the

slot (w). Experimental results and calculations from the theoretical solutions have determined the effects of varying electrical and physical parameters. The results of this work are presented graphically in Refs. 1, 2, 3, 5, and 6.

These results show that if the physical parameters of the slot line and the slot wavelength are held constant, the values of the parameters λ'/λ, v/v_g, Z_o, and f are nearly the same for computations using electric walls and computations using magnetic walls if the value of b/d is greater than 7.5, however they diverge as b is made smaller. The wavelength ratio decreases with increasing frequency, increases slightly with increasing slot width, and decreases rapidly as d/λ increases. Similarly, the characteristic impedance (Z_o) decreases at the top and bottom end of the frequency range and increases with increasing slot width or decreasing substrate thickness.

For the coaxial line-to-slot line transition, theoretical calculations for $B_{in} = 0$ at 9.1 GHz and for $B_{in} = 0$ at 6.21 GHz given in Ref. 4 give a VSWR of less than 2:1 from well below 1 GHz to 10 GHz. This has been verified from 4 GHz to 8 GHz by Robinson and Allen. Measurements from 10 MHz to 12 GHz by this author showed VSWR less than 2.0 from 1.2 GHz to 10 GHz.

No measurements of insertion loss are reported in the literature. Experimental measurements of insertion loss including the coaxial line-to-slot line transitions were made over the same frequency range. Details of experimental results are presented in Section V.

III. CONSTRUCTION TECHNIQUES

In the course of this research an intensive investigation of available materials and suitable construction techniques was conducted. A number of sources of materials were discovered and several acceptable construction techniques were tested.

A. MATERIALS

The substrate material used for slot line must have a high dielectric constant (usually greater than 9), and a low loss tangent. For some applications it is also necessary that the material be easy to machine. Three substrate materials were found that meet the requirements for a high dielectric constant and low loss tangent, beryllia, alumina and Custom K-707, a silicone base dielectric.

Beryllia and alumina have nearly identical dielectric constants and loss tangents. Beryllia has a better thermal conductivity than alumina but it produces a toxic dust so it was never seriously considered for this research.

Alumina has a dielectric constant of from 9.6 to 9.8 depending on the purity of the material. It is readily available in small quantities from a number of manufacturers. The major disadvantages to alumina are that it is only available in a 25 mil thickness, except on special order, and it requires diamond tipped tools for machining.

The Custom K-707 substrate material, manufactured by Custom Materials, Inc., Chelmsford, Mass., is available in several thicknesses with dielectric constants ranging from 3 to 25. The major disadvantage for this project was a minimum order requirement which made the cost prohibitive. It is available with either one or both sides copper clad.

The only metalization available on the alumina substrate material is gold. Gold metalization requires use of extremely volatile chemicals for etching and the metalized substrate costs nearly three times as much as the unmetalized substrate.

Adhesive backed copper foil manufactured by Circuit-Stik, Inc., Gardena, Calif., is an economical metalization for slot line research. This material has a conductive adhesive so that the total thickness of the foil and adhesive can be used as the conductor thickness in calculations with good results. The copper is easily etched using conventional techniques and has the added advantage that it can be removed easily so the substrate can be re-used. It can also be soldered, although some care must be used to avoid excessive heat.

Mariani [Ref. 2] suggests the use of an adhesive backed aluminum tape. The dielectric adhesive used on this tape will cause some error in calculations if it is ignored. Aluminum is also difficult to solder but this can be overcome by using a conductive epoxy instead of solder. If facilities for vacuum deposition of aluminum are available,

this metalization is worthy of consideration for further research with slot line.

B. CONSTRUCTING THE SLOT

Early attempts at constructing the slot with a slotting saw in a milling machine showed that it was extremely difficult to cut completely through the metalization without cutting into the substrate. While this slight cut would have a negligible effect on the performance of the slot line, it was feared that, in the case of a ceramic substrate such as alumina, this would blunt the edge of the saw blade and cause it to gouge the edges of the slot.

Photoetched slots showed no problems with ragged edges or undercutting. The major problem encountered with locally sensitized boards was some difficulty in getting the board to develop properly. Perhaps this problem could be eliminated by oven drying the photoresist or use of centrifuge facilities such as those at Monterey Peninsula College to apply the photoresist.

Negatives for photoetching can be made by applying printed circuit layout tape on clear celluloid or by reproducing lines drawn on slick finish paper with a draftsman's ruling pen on the 3-M Thermofax machine as transparencies. The printed circuit tape is available in widths of 15, 20, 31, 40, and 62 mils with a tolerance of less than ±1 mil in width.

It is possible, with a reasonable amount of care, to lay down two pieces of either aluminum tape or the copper

foil, separated by a small gap to form the slot. Using the printed circuit layout tape as a spacer, it is possible to form a slot within ±1 mil of the tape width. These tolerances are comparable to those obtained with other methods. Mariani [Ref. 2] shows that the effect on characteristic impedance of a ±1 mil error in a slot width is negligible.

IV. MEASUREMENT TECHNIQUES

Any investigation into the characteristics of a type of transmission line requires the measurement of three parameters: attenuation, VSWR, and slot wavelength. From these measured parameters it is possible to determine the major characteristics of the line.

A. ATTENUATION

The simplest measurement to make on the slot line is attenuation. The circuit in Figure 6 was found to provide easily repeatable measurements with acceptable accuracy. A coaxial directional coupler was used to monitor the input power and, since low power levels (less than +10 dBm) were

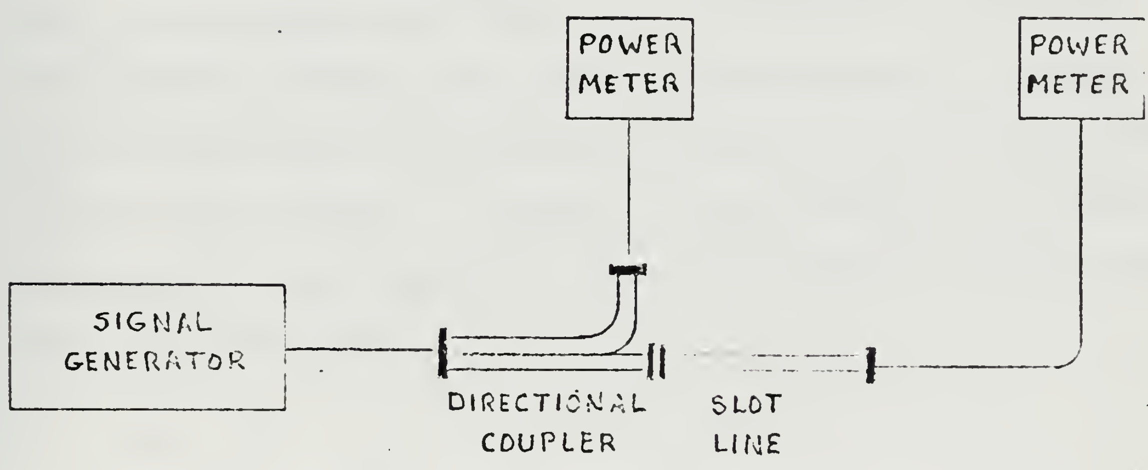

Figure 8. Attenuation Measurement Circuit Diagram.

used, the thermistor mount of the output power meter was used as the load.

Sources of error in this circuit are the coaxial adaptors needed between the directional coupler and the miniature coaxial line used for the coaxial-to-slot line transition, the coaxial adaptors required between the miniature coaxial line and the thermistor mount, and the imperfect directivity of the directional coupler. Catalog values for these losses showed that their effect would be negligible. A single set of measurements made with this circuit results in a total attenuation value for the slot line, two coaxial line to slot line transitions, and the attenuation of two sections of miniature coaxial line.

For a good match, the losses in the coaxial line-to-slot line transition will be negligible. The 85 mil miniature coaxial line, however, has an attenuation ranging from 0.064 dB per foot at 100 MHz to 0.8 dB per foot at 12 GHz. This is not always negligible and the effects of it could be overcome by making two sets of measurements on a slot of the same width and dielectric substrate measurements but of differing lengths. However, in this report the effects of connector and transition losses are lumped together with the slot line losses.

B. VSWR

Mariani [Ref. 2] used a block of polyiron material as a load in order to measure the VSWR of a single coaxial-to-slot line transition. For this research a simpler circuit

was employed [Fig. 9]. A coaxial 50 ohm termination was used for Z_L. Type N-to-type OSM coaxial adaptors were required for this circuit and it included two transitions instead of one. (The coaxial adaptors were low VSWR [1.07 + 0.008f GHz max] and, by assuming that the two transitions are identical, reasonable accuracy can be obtained with this circuit.)

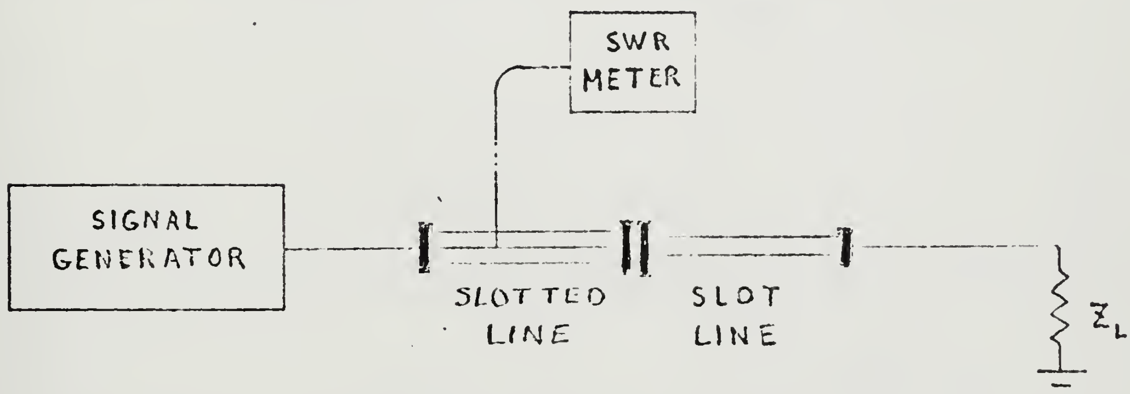

Figure 9. VSWR Measurement Circuit Diagram.

C. SLOT WAVELENGTH

Mariani [Ref. 2] describes a method for using a sliding steel rule to find resonance in order to measure slot wavelength. The same circuit that was used for VSWR measurements was used to measure slot wavelength with good results. If Z_L is made a short circuit, and the slotted line carriage set on a voltage minimum, a calibrated steel rule can be slid along the slot to find successive minimums.

It appears that it would be possible to use a magnetic coupling loop or an electric probe inserted from the side

of the slot in order to measure slot wavelength directly. Attempts to probe the slot from above with an electric probe slightly offset from the slot centerline were unsuccessful. The E-field component perpendicular to the slot in this region was so small that the probe had to penetrate close to the slot in order to obtain sufficient coupling. This resulted in a large perturbation of the fields in the slot which prevented obtaining useful results.

V. EXPERIMENTAL RESULTS

It has been stated [Ref. 1, 2, 3, and 4] that the coaxial line-to-slot line transition is a broadband transition but no experimental evidence was presented to indicate the frequency range implied by the term broadband. This research covered the spectrum between 10 MHz and 12 GHz in an effort to determine what this frequency range was. Slot line theory also indicates that, even though the slot wave is non-TEM, no cutoff frequency exists. Since the RF energy is closely confined to the slot, it appears that grounding the foil on both sides of the slot will force a cutoff at some frequency.

A. SUPPORTING JIGS

In an effort to find a cutoff frequency when the foil on both sides of the slot was grounded, two supporting jigs were constructed to facilitate connecting the foil to ground. The first of these jigs [Fig. 10] had a cavity under the slot with dimensions chosen so that, if the top were covered with a conductor, it would appear as a waveguide below cutoff over the frequency range of interest. Measurements showed that this jig exhibited a cavity effect at some frequencies, so a second jig was constructed. This jig [Fig. 11] had no effect on the slot line measurements. This jig was used in obtaining all of the attenuation and VSWR data presented. No supporting jig was used in obtaining the slot wavelength data.

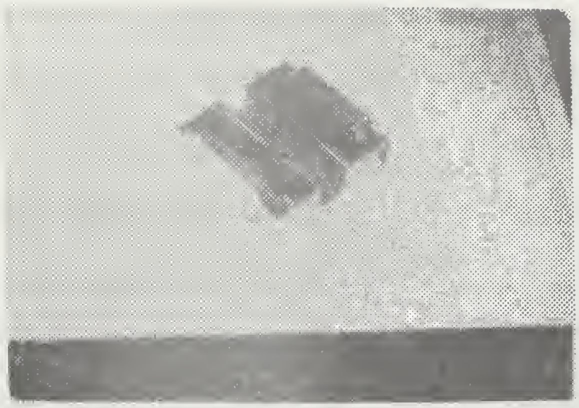

Figure 10. Unsuccessful Supporting Jig.

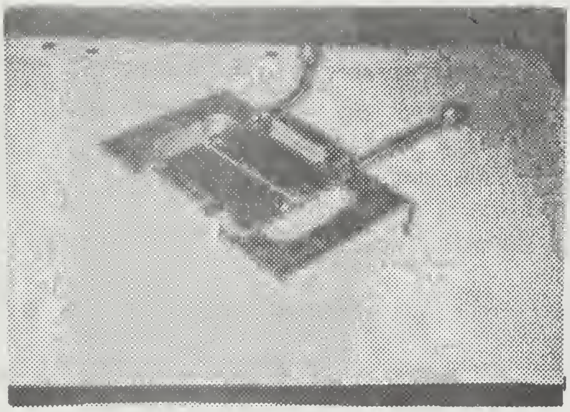

Figure 11. Successful Supporting Jig.

B. ATTENUATION

Two 4-inch sections of 85-mil coaxial line were used as transitions into and out of a 2-inch section of slot line. The 31-mil slot width used for these measurements was chosen as a first approximation to the value required to match the 50 ohm coaxial line. No attempt was made to optimize the slot width. Linear extrapolation of the curves presented in Ref. 2 indicates that this slot has a characteristic impedance of about 130 ohms, or nearly twice that required for a good match. Sample calculations with Eqn.6 show a wide variation in results for different values of b, the spacing of the electric or magnetic walls.

The results presented in Fig. 12 indicate that this configuration has acceptable losses between about 400 MHz and 8 GHz. There are indications of a resonance effect in the vicinity of 6.5 GHz. This is believed to be due to the fact that the distance between the two transitions is near one slot wavelength in this region. The attenuation also increases rapidly below 250 MHz and above 10 GHz. It is not apparent if this effect is caused by the bandwidth limitations of the transitions or those of the slot. End effects due to the short slot also cause some uncertainty as to the cause of the increased attenuation at the low end of the frequency range.

C. VSWR

Figure 13 shows that the configuration tested has a VSWR less than 2:1 between 1 and 10 GHz. Due to equipment

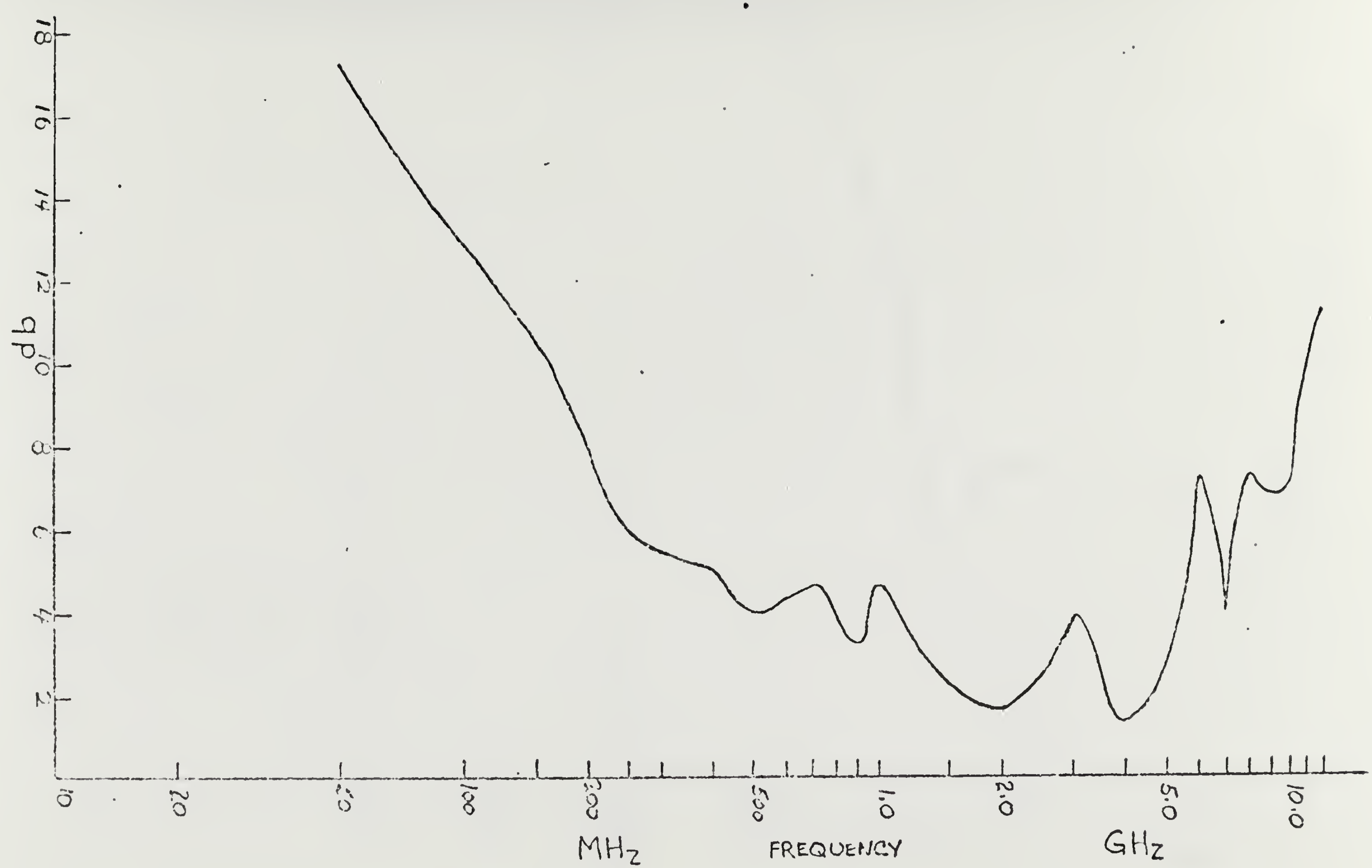

Figure 12. Attenuation vs Frequency.

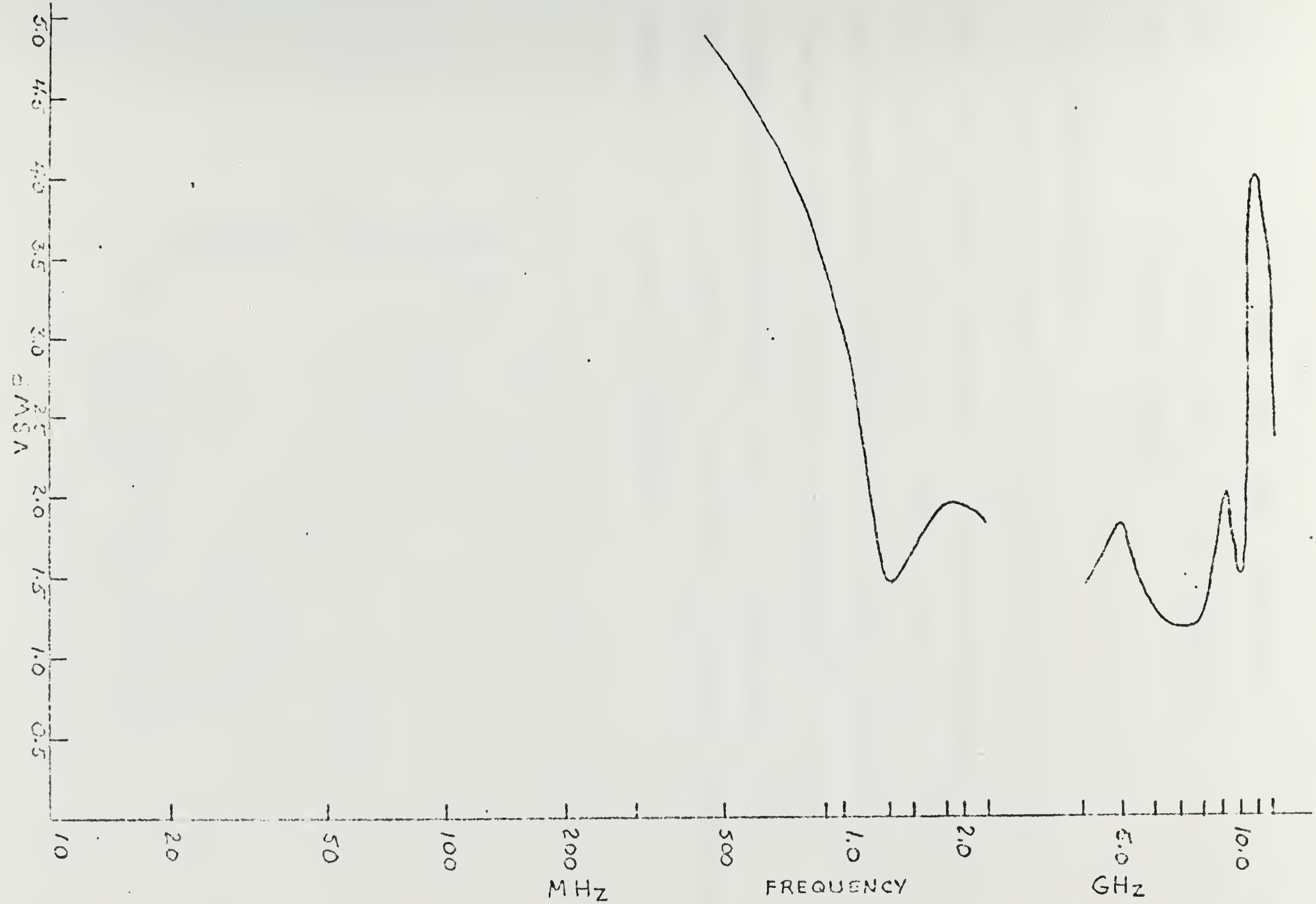

Figure 13. VSWR vs Frequency.

limitations it was impossible to obtain VSWR measurements between 2.3 and 4 GHz. The VSWR measurements in the vicinity of 6.5 GHz confirm that the high attenuation in this region was a resonance effect.

D. SLOT WAVELENGTH

The slot wavelength measurements presented in Fig. 14 are for a 20-mil slot width. Slot wavelength varied from .56 λ_o to .70 λ_o in X-band. These results are consistent with theoretical predictions of a linear dependence on frequency within the limits of experimental accuracy. Slot length was approximately $\lambda'/2$ at 2.2 GHz and $\lambda'/4$ at 1.1 GHz. Below the $\lambda'/4$ frequency, end effects dominate the measurements and λ' cannot be measured.

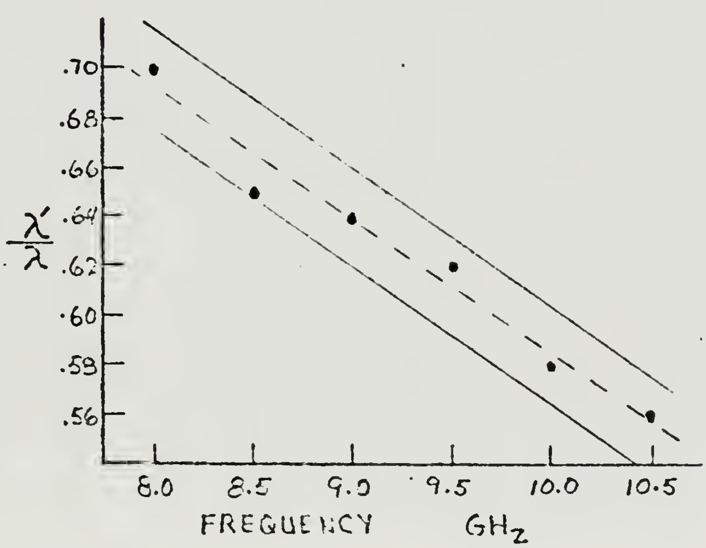

Figure 14. Wavelength Ratio vs Frequency.

Attempts were made to construct two K-band coaxial-to-waveguide adaptors in order to permit measurements at K-band. Due to excessive reflections from the coaxial connectors and the very sharp tuning of the sliding shorts used in the adaptors, these efforts were unsuccessful.

VI. CONCLUSION

Sample sections of a slot transmission line were constructed and tested. Several construction and measurement techniques were evaluated and found satisfactory.

At the low frequency end of the spectrum VSWR and insertion loss both increase monotonically. It was not determined, however, if this effect was a result of the limited bandwidth of the coaxial-to-slot line transition, end effects due to the short section of slot line tested, or a result of properties of the slot line. At 400 MHz, 3 db of the 5 db insertion loss may be accounted for by the VSWR of 6.0. At midband, VSWR was low enough that most of the attenuation can be assigned to the slot line. The rapid increase in both attenuation and VSWR above 10 GHZ suggests reflections at the connectors or transitions rather than increased slot line losses. Nevertheless, the useful bandwidth is potentially several octaves, from UHF through X-band.

The slot line is a practical form of planar transmission line and should find many applications in miniaturized microwave systems. It also shows promise of being adaptable to application as a flush mounted antenna.

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13. ABSTRACT

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SLOT LINE						
TRANSMISSION LINE						

Thesis 136184
Z247 Zavadil
c.1 Slot transmission line.